LAMINATED COMPONENT FOR FUSION REACTORS

5 ## Background of the Invention:

Field of the Invention:

The invention relates to a highly heat-resistant laminated component for a fusion reactor. The component has at least one plasma-facing area made of tungsten or a tungsten alloy with a

10 tungsten concentration of > 90 % by weight, a heat-dissipating area made of copper or a copper alloy with conductivity of > 250 W/mK and a mean grain size of > 100 µm, and an area lying in between and being formed of a refractory-metal-copper composite.

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For stationary fusion reactor operation, power flows of up to 10 MW/m^2 can be expected in the area of the surface of first-wall components, which are also referred to as PFCs (plasma facing components). In the event of plasma breakdown,

20 approximately 20 GJ may be released at certain points within only a few milliseconds. The development of PFCs designed specifically for use in areas of maximum energy concentration, such as diverter, baffle and limiter areas, represents a key element in the technological implementation of the results of

25 fusion research.

The material requirements applicable to PFC components are diverse and often conflict with one another. In addition to physical and mechanical properties such as high thermal conductivity, high melting point, low vapor pressure, good

5   thermal-shock resistance and suitability for processing, use in nuclear fusion poses special requirements, including low activation and transmutation under heavy neutron exposure, low continuous tritium absorption, low erosion by plasma ions and neutron particles, low sputter rate and erosion resulting from

10   local effects such as arcs and hotspots as well as low cooling of core plasma through characteristic radiation.

Depending upon the specific load conditions, the preferred materials for PFCs are beryllium, carbon-fiber-reinforced

15   carbon (CFC), and tungsten. Tungsten is particularly well suited for use in the first wall, where relatively low plasma temperatures and high particle densities prevail. Tungsten has very good thermal properties such as high thermal conductivity (165 W/mK at room temperature). Moreover, its high melting

20   point, low tritium absorption capacity, low vacuum gas rate and low sputter rate virtually predestine tungsten for use in PFCs. In order to achieve effective heat removal in areas of extreme energy density, PFCs must be actively cooled. This can be accomplished with the aid of copper components filled with

25   circulating coolant, which are combined as a heat sink with the tungsten components. To achieve sufficiently high

mechanical stability and rigidity, it is advantageous to join

the copper heat sink with a highly rigid metallic structural

material. Austenitic steels and particle-reinforced copper

alloys, such as age-hardened Cr-Zr alloyed copper alloys (Cu-

5   Cr-Zr) or ODS (oxide-dispersion-strengthened) copper materials

(e.g. $Cu-Al_2O_3$, $Cu-ZrO_2$, $Cu-Y_2O_3$, Cu-rare-earth-oxide) are

suitable for reinforcing elements of this kind. Two design

variations are considered for PFCs to be used in areas of high

energy density. In so-called flat tiles, the transitions

10   between the individual materials are nearly uniform. In

monoblock components, sufficient structural stability and

rigidity are provided by the tube filled with circulating

coolant, which may consist, for example, of an age-hardened

copper alloy or ODS copper. Toward the outside, the other

15   materials are arranged in a configuration comparable to that

of the flat-tile variation. The tungsten segment is a cube-

shaped body that surrounds the cooling tube, whereby a buffer

layer consisting of a soft, ductile materials, preferably pure

copper with a low oxygen content (OFHC copper) is placed

20   between the cooling tube and the tungsten segment.

A particular difficulty encountered in the production of

laminated parts for fusion reactors, such as flat-tile or

monoblock components, is that tungsten and copper exhibit very

25   different heat expansion behavior. The heat expansion

coefficient of tungsten at room temperature is 4.5×10^{-6} K^{-1}, while that of copper is 16.6×10^{-6} K^{-1}.

Technologies recommended for bonding tungsten to copper
5   include diffusion welding and back-casting. Diffusion welding can be performed using hot isostatic pressing (HIP) as described in European patent specification EP 1 025 938. The processes cited above are performed within a temperature range of approximately 700 to 1300°C.
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During cooling, stress builds up in the vicinity of the joint as a result of the different heat expansion coefficients of tungsten and copper. Stresses are also induced when PFCs are used, however, as they are exposed to cyclical heat loads.
15 These stresses can cause cracking or separation at the tungsten to copper interfaces. This hinders thermal dissipation and thus poses the danger that the laminated component will melt. Extensive development programs have been initiated, some of which have already been completed, for the
20 purpose of realizing a laminated component consisting of a plasma-facing tungsten segment bonded form-fitting with an actively cooled copper heat sink which exhibits low bonding stresses in the interface area.

25 A significant reduction in stresses was achieved by designing the tungsten segment as a group of individual small cubes or

rods with side lengths or a diameter of several millimeters, whereby the cubes or rods are inserted into a copper segment. This form of segmentation reduces thermal stresses resulting from the bonding process and from cyclical operation. However,

5   the design also poses a high risk of fatigue cracking in the tungsten-copper interface.

Numerous attempts have been made to reduce tensions in the interface by incorporating a graded interlayer between the

10   tungsten and copper segments.

Thus, U.S. Patent No. 5,126,106, for example, describes a method for producing a tungsten-copper FGM (functionally graded material) in which a tungsten segment with graded

15   porosity, produced by thermal plasma spraying, for example, is infiltrated with copper.

U.S. Patent No. 5,988,488 also describes a production process in which thermal plasma spraying is used to achieve a graded

20   interlayer between the tungsten and copper segments.   In contrast to the process described in U.S. Patent No. 5,126,106, the copper phase is also separated by thermal plasma spraying, whereby the specific powder blend added contains corresponding proportions of tungsten and copper. A

25   thin metallic film between the tungsten and the FGM promotes adhesion.

U.S. Patent No. 5,988,488 also contains a description of an attempt to insert a layer consisting of a blend of copper and tungsten between the tungsten and the copper heat sink by

5 brazing or diffusion bonding. However, the difference in the heat expansion coefficients was too great. No further detailed explanations are provided in this patent.

It can be assumed that the production processes described in

10 both, U.S. Patent No. 5,126,106 and U.S. Patent No. 5,988,488 produce laminated parts that exhibit significantly higher resistance to thermally induced cracks. However, the disadvantage of the processes described in these patents is that they are complicated and, consequently, the parts

15 produced in the manner described are very expensive. Moreover, due to process engineering constraints, the technologies cited above are applicable to flat-tile structures only. Generally speaking, their use in the production of monoblock geometries is impossible for geometric reasons.

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Summary of the Invention:
It is accordingly an object of the invention to provide a laminated component for a fusion reactor which overcomes the above-mentioned disadvantages of the heretofore-known devices

25 and methods of this general type and which provides for laminated components for fusion reactors consisting at least

in part of tungsten or a tungsten alloy and copper or a copper
alloy which exhibit sufficient functional capacities,
particularly with respect to thermal fatigue, which can be
produced cost-effectively, and which are suitable for
5   monoblock geometries.

With the foregoing and other objects in view there is
provided, in accordance with the invention, a highly heat-
resistant laminated component for a fusion reactor,
10 comprising:

a plasma-facing area made of tungsten or a tungsten alloy with
a tungsten concentration of > 90 % by weight, a heat-
dissipating area of copper or a copper alloy with a thermal
conductivity of > 250 W/mK and a mean grain size of > 100 μm,
15 and an area in between the plasma-facing area and the heat-
dissipating area of a refractory-metal-copper composite;

the refractory-metal-copper composite having a macroscopically
uniform copper and tungsten concentration progression and a
refractory metal concentration x of 10 vol.% < x < 40 vol.%
20 throughout a thickness d of 0.1 mm < d < 4 mm, and a
refractory metal phase forming a virtually continuous
skeleton.

Refractory-metal-copper components are used in many industrial

applications as heat sinks or heat spreaders, in electronic

packages, for example. Refractory metals are elements in

groups IV^b and V^b of the periodic table of elements which have

5   a melting point above 1800°C - specifically the metals Nb, Ta,

Cr, Mo, and W.

Contrary to the widespread conception that stresses in

tungsten-copper laminated components for fusion reactors can

10   be reduced only with the use of FGMs, experiments surprisingly

showed that interlayers composed of refractory-metal-copper

materials with a macroscopically uniform copper-refractory-

metal concentration progression can also be used effectively.

A macroscopically uniform concentration progress is defined as

15   the concentration progression throughout the thickness of the

refractory-metal-copper composite without regard for

microscopic differences in concentration. Microscopic

differences in concentration always appear in refractory-

metal-copper composites, since refractory metals and copper

20   are insoluble or soluble only to a small extent in each other.

Thus one finds copper and refractory-metal phase areas next to

one another in sizes of between 5 and 50 μm.

An effective reduction of stresses in the interface area is

25   can only be achieved if the layer consisting of a refractory-

metal-copper composite is at least 0.1 mm thick. Thinner

layers do not provide for sufficient tension reduction. While

thicknesses of 4 mm and above do not impair the functional

capacity of the laminated part in terms of resistance to

separation and thermally induced fatigue cracking, heat

5   dissipation is reduced by virtue of the poorer thermal

conductivity of the refractory-metal-copper composite to the

extent that the functional reliability of the laminated part

is not longer ensured.

10 A further prerequisite for sufficient functional capacity is

that the refractory metal concentration in refractory-metal-

copper composites must lie between 10 and 40 % by volume.

Process reliability is not sufficiently ensured at either

higher or lower refractory metal concentrations. Furthermore,

15 the refractory-metal-copper composite must be produced in such

a way that the refractory-metal phases form a nearly

continuous skeleton.

This requirement is met by refractory-metal-copper composites

20 produced using power-metallurgical processes, such as the

infiltration of a porous refractory-metal body with copper.

The porous refractory-metal body can be a shaped or sintered

object. Refractory-metal-copper composites with nearly

continuous skeletons can also be produced by pressing powder

25 mixtures or composite powders and sintering. Aside from W-Cu

and Mo-Cu composites produced in this way, the use of rolled

or extruded Mo-Cu composites has proven to be particularly

advantageous. Furthermore, the copper or copper-alloy segment

must be capable of sufficiently reducing thermally induced

stresses. Given the selection criterion of "thermal

5   conductivity > 250 W/mK", only copper materials with a low

concentration of alloy elements and a correspondingly low

yield strength can be used. In addition, the copper or copper-

alloy segment must have a mean particle size of more than 100

μm in order to ensure effective stress reduction. The bonding

10   of the copper or copper-alloy segment using OFHC (oxygen-free-

high-conductivity) copper by back-casting it to the

refractory-metal-copper composite has proven highly

advantageous. This process ensures that the mean particle size

in the copper / copper-alloy segment is always greater than

15   100 μm. The bonding of the tungsten / tungsten-alloy segment

with the refractory-metal-copper composite segment by melting

the copper phase can be accomplished during the same process

phase. It has proven advantageous to introduce a copper foil

or sheet with measuring between 0.005 and 0.5 mm in thickness

20   between the tungsten and the refractory-metal-copper

composite. In order to improve the bond between tungsten and

copper, it is also advantageous to introduce a metallic

element or alloy – by coating the tungsten substrate, for

example – which is soluble in both tungsten and copper or

25   which reacts with these two materials. Elements or alloys of

the ferrous metals group, such as nickel, are suitable for this purpose.

Suitable tungsten materials for the plasma-facing segment
5 include monocrystalline tungsten, pure tungsten, AKS (aluminum-potassium-silicate doped) tungsten, UHP (ultra-high-purity) tungsten, nanocrystalline tungsten, amorphous tungsten, ODS (oxide-dispersion-strengthened) tungsten, W-Re, ODS-W-Re and carbide-, nitride, or boride-precipitation-
10 hardened tungsten alloys with preferred a carbide, nitride or boride concentration of between 0.05 and 1 vol.%. Segmentation of the tungsten / tungsten-alloy components is advantageous. As the crack propagation rate of the tungsten components is significantly higher in the direction of deformation than
15 perpendicular to it, it may be advisable in the case of parts exposed to high levels of stress to produce the tungsten parts in such a way that the direction of deformation is perpendicular to the plasma-facing surface.

20 In order to achieve sufficient structural stability and rigidity, a component consisting of a metallic material with a strength of more than 300 MPa is bonded to the copper segment. Particularly suitable metallic materials include age-hardened Cu-Cr-Zr, and ODS-Cu materials as well as austenitic steels.
25 The selection of the most suitable bonding method depends upon the type of materials paired. Copper-copper or copper-steel

pairings are best bonded using hard soldering or diffusion

bonding techniques, such as hot isostatic pressing. Also

suitable for copper-copper pairings are such melt-welding

processes as high-energy electron-beam welding.

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Other features which are considered as characteristic for the

invention are set forth in the appended claims.

Although the invention is illustrated and described herein as

10   embodied in a laminated component for fusion reactors, it is

nevertheless not intended to be limited to the details shown,

since various modifications and structural changes may be made

therein without departing from the spirit of the invention and

within the scope and range of equivalents of the claims.

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The construction and method of operation of the invention,

however, together with additional objects and advantages

thereof will be best understood from the following description

of specific embodiments and examples, when read in connection

20   with the accompanying drawings.

Brief Description of the Drawings:

Fig. 1 is a perspective view of a diverter component produced

as a flat-tile as described in Example 1;

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Fig. 2 is a cross-section of the material sequence as described in Examples 1 and 2;

Fig. 3 is a perspective view of the mechanically processed
5   intermediate product following back-casting, as described in Example 1;

Fig. 4 is a perspective view of a diverter component produced as a monoblock as described in Example 2; and
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Fig. 5 is a perspective view of a diverter component produced as a monoblock as described in Example 2 prior to bonding with the Cu-Cr-Zr tube

15   Detailed Description of the Preferred Embodiments:

Example 1:
A diverter plate 1 for fusion reactors was produced as a flat tile (see Fig. 1).

20   In the first step, tungsten tiles 2 measuring 20 x 40 x 6.5 mm were cut from a tungsten rod with a diameter of 60 mm. The tiles were cut from the rod in such a way that the tile height (6.5 mm) is parallel to the rod axis. Thus the particles are aligned in the direction of subsequent main heat flow. An
25   intermediate tile 3 with a thickness of 2 mm, a width of 20 mm

and a length of 40 mm was then cut from a plate consisting of a tungsten-copper composite with a copper concentration of 15 % by weight (designation T 750).

5   In a suitable casting unit, a tungsten tile 2, an OHFC copper foil measuring 0.10 mm in thickness 6, the T 750 intermediate tile 3 and an OFHC-copper block 4 measuring 20 x 40 x 10 mm were stacked. The stack was then back-cast with OHFC copper in an inert-gas oven in a hydrogen atmosphere at a temperature of
10   1250°C. That temperature was maintained for 30 minutes, ensuring sufficient coverage of the molten copper on all of the solid components of the structure.

     Following removal of the back-cast stack from the back-casting
15   unit, the stack was milled on all sides. In the process, the back-cast copper was milled down to a residual thickness of 2 mm (see Fig. 3). In order to remove undesired copper deposits, the other surfaces were also milled on all sides.

20   Subsequent ultrasonic testing and a metallographic probe taken from a the joint zone of a parallel sample showed that a solid material bond was formed in the entire stack during the cooling phase once the temperature fell below the copper melting point.

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Using the process described in the above-noted European patent

specification EP 1 025 938, the laminated tiles produced in

the back-casting process described above were joined with a

Cu-Cr-Zr heat sink 5 in which the cooling structure 7 was

5   worked in mechanically after removal from the HIP unit. The

material sequence of the components is illustrated

schematically in Fig. 2.

Example 2:

10   The diverter plate 1 shown in Fig. 4 was produced in monoblock

design in a similar process.

A passage with a length of 10 mm and a diameter of 15.2 mm was

bored through the center a block of tungsten 2 measuring 30 x

15   20 x 10 mm.

A ring 3 with an outside diameter of 15 mm, a wall thickness

of 1 mm and a length of 10 mm was made from a plate consisting

of a tungsten-copper composite with a copper concentration of

20   20 % by weight (designation T 800).

An OHFC copper foil with a thickness of 0.1 mm, the ring 3

made from T 800 and a 15 mm long OFHC copper rod with a

diameter of 13 mm were introduced into the passage bored

25   through the tungsten block in accordance with the material

sequence shown in Fig. 2. The tile bore was then back-cast

with OFHC copper in an inert-gas oven in a hydrogen atmosphere at a temperature of 1250°C for 30 min. After removal of the back-cast monoblock, a bore with a diameter of 12 mm concentric with the bore in the tungsten block was drilled

5   into the back-cast copper. Upon completion of this processing phase, the laminated block exhibited an OFHC copper layer 4 with a thickness of 0.50 mm in the bore (see Fig. 5). The components produced in this way were joined with a Cu-Cr-Zr tube 5 with an outside diameter of 12 mm in an HIP process.

10   The cooling structure 7 was introduced mechanically following removal from the HIP unit. Subsequent ultrasonic testing and metallographic analysis showed perfect bonding of the parts of the laminated component produced in this way.

15   This application claims the priority, under 35 U.S.C. § 119, of Austrian patent application AT/GM 228/2003, filed April 2, 2003; the disclosure of the prior application is herewith incorporated by reference in its entirety.